

## GAMMA RAYS FROM 'HIDDEN' MILLISECOND PULSARS

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**Abstract**

We study the properties of a new class of gamma-ray sources consisting of millisecond pulsars totally or partially surrounded by evaporating material from irradiated companion stars. Hidden millisecond pulsars offer a unique possibility to study gamma-ray, optical and radio emission from vaporizing binaries. The relevance of this class of binaries for GRO observations and interpretation of COS-B data is emphasized.

**1. Introduction**

The missing link between low mass binaries (LMXBs) containing rapidly rotating neutron stars and binary millisecond pulsars has been provided by the discovery of pulsars in the process of vaporizing their very low-mass companion star. Two such systems are currently known: PSR 1957+20 with spin period  $P = 1.6$  msec (Fruchter, Stinebring and Taylor, 1988) and PSR 1744-24A with  $P = 11.6$  msec in the globular cluster Terzan 5 (Lyne et al., 1990; Nice *et al.*, 1990). PSR 1957+20 is the prototype of SVPs with stable eclipse properties (type I) whereas PSR 1744-24A shows a more erratic and sometimes intermittent behavior of radio-eclipses characteristics of a second class of SVPs (type II). In addition to these two SVP-classes, a third class of SVPs is expected on theoretical grounds (type III). The SVPs of type III are completely enshrouded by the evaporated material from the irradiated companion star, and they are therefore 'hidden' pulsars because their radio-emission may be completely blocked. However, they might be revealed by X-ray/gamma-ray emission produced by the interaction of the pulsar wind with evaporating material at the termination shock (Tavani, 1991b,c).

The existence of 'star-vaporizing pulsars' (SVPs) is in agreement with an evolutionary scenario of low-mass binaries containing compact stars whose energetic radiation (X-rays and  $\gamma$ -rays) illuminates their companion stars and drives a strong evaporative mass outflow during the LMXB and post-accretion evolutionary phases (Ruderman, Shaham and Tavani, 1989, hereafter RST; Tavani, 1989,1991a,b,c). Further 'vaporization' of the companion star in the post-accretion phase is caused by radiation produced by the interaction of the pulsar wind with the outflowing material from the companion. It is precisely this evolutionary phase that leads to the formation of a new class of  $\gamma$ -ray sources consisting of hidden millisecond pulsars. We follow here the discussion of hidden millisecond pulsars presented in Tavani (1991c), with emphasis on their gamma-ray emission (Tavani, 1991f).

## 2. Three Classes of Star-Vaporizing Pulsars

Pulsar emission in the form of a Poynting flux and a relativistic particle wind is possible if  $r_{lc} < r_b$ , with  $r_{lc}$  the light-cylinder radius  $r_{lc} = c/\Omega = (4.77 \cdot 10^6 \text{ cm}) \cdot P_{-3}$ , where  $P_{-3} = P/(10^{-3} \text{ sec})$ , and  $r_b$  the distance from the pulsar at which the material outflowing from the companion star is stopped by radiation or magnetic pressure. For the cases considered in this paper,  $r_b = a - R_s$ , with  $a$  the orbital distance, and  $R_s$  the distance from the companion star at which the ram pressure of the outflowing gas is balanced by the radiation pressure from the pulsar. For SVPs,  $r_s$  is in the range  $r_{lc} < r_s < a$ , and satisfies the relation  $L/(4\pi r_s^2 c) = \alpha \dot{m} v_g / (2\pi r'^2)$  with  $L$  the pulsar luminosity,  $r$  the distance from the pulsar,  $c$  the speed of light,  $\dot{m} = |\dot{m}|_{rad}$  the mass loss from the irradiated companion star,  $r' = a - r_s = R_s$  the distance from the companion,  $\alpha$  a dimensionless quantity giving the hydrodynamical density enhancement near  $R_s$  relative to the density obtained from a  $1/r'^2$  ideal dependence for constant wind velocity<sup>1</sup>, and  $v_g$  the gas velocity. Since the wind velocity of radiation-driven mass outflows in SVPs and LMXBs is of the same order of magnitude of the escape velocity from the star  $v_e$  (Tavani and London, 1991) and since the Keplerian orbital velocities  $v_K$  of low-mass binaries with orbital periods  $P_{orb} \lesssim 1$  day are comparable with  $v_e$ , we can write the pressure balance equation as follows

$$\mathcal{K} F[x] = \dot{m} \quad (1)$$

where we defined  $x = r_s/a$ ,  $\mathcal{K} = L\sqrt{a}/(2c\alpha\sqrt{GM_1}) \simeq (1.53 \cdot 10^{17} \text{ g s}^{-1})\sqrt{a_{11}}\dot{P}_{-20}I_{45}/(\alpha P_{-3}^3)$ , with  $\dot{P}_{-20}$  given by  $\dot{P} = 10^{-20} \dot{P}_{-20} \text{ s s}^{-1}$ ,  $I_{45}$  the neutron star moment of inertia in units of  $10^{45} \text{ g cm}^2$ ,  $a = 10^{11} a_{11} \text{ cm}$ , and  $M_1$  the pulsar mass. The function  $F[x]$  is given by

$$F[x] = (1 - x)^{3/2} x^{-2} \quad (2)$$

Eqs. (1) and (2) give the position of the shock radius as a function of  $\dot{m}$ , orbital ( $a_{11}$ ,  $M_1$ ), pulsar ( $\dot{P}_{-20}$ ,  $P_{-3}$ ) and hydrodynamics ( $\alpha$ ) parameters.

It is also useful to write the radiation-driven mass loss rate (in cgs units) as (RST)  $\dot{m} = 10^{-17} f L \Delta = (3.95 \cdot 10^{16} \text{ g s}^{-1}) f \dot{P}_{-20} I_{45} \Delta_{-2} / P_{-3}^3$ , where the quantity  $f$  depends on the net heating and hydrodynamics of the mass outflow near the companion star (Tavani 1989), and with  $\Delta \equiv [R_*/(2a)]^2$  (and  $\Delta = 10^{-2} \Delta_{-2}$ ) the solid angle subtended by the companion star to the primary where  $R_*$  is the companion radius. For typical fluxes irradiating SVP companions we have  $f \sim 0.1\Upsilon$ , where  $\Upsilon$  is a dimensionless spectral ‘quality’ parameter which gives the efficiency of energy deposition. For the two energy bands which are effective in driving a strong wind, we obtain  $\Upsilon \sim 10 - 100$  for soft X-rays and  $\Upsilon \lesssim 0.2$  for hard X-rays and  $\gamma$ -rays (Tavani, 1989).

We can then rewrite the pressure balance condition Eq. (1) in a form which, in first approximation, is independent of the pulsar luminosity and depends upon the spectral ‘quality’ of the heating  $f$  as well as upon  $\alpha$  and orbital parameters

$$F[x] = 0.258 f \alpha \Delta_{-2} \sqrt{M_{1.4} a_{11}^{-1/2}} \quad (3)$$

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<sup>1</sup>Results of a hydrodynamical calculation of the outflow in the case of PSR 1957+20 and PSR 1744-20A gives  $1 \lesssim \alpha \lesssim 10$  (Tavani and Brookshaw, 1991).

Given the variety of pulsar luminosities and orbital parameters of low-mass binaries we can expect several types of SVPs characterized by different  $R_s$ 's and shapes of the mass outflow influenced by the combined action of gravitational, radiation and Coriolis forces.

SVPs of type I are obtained when  $\dot{m}$  is close to  $\dot{m}_1 \equiv \mathcal{K}F[1 - R_*/a]$  and the Coriolis forces acting on the wind particles near  $R_s$  are not large enough to produce an appreciable tangential component of the gas pressure. The radio eclipses expected for type I SVPs are sharply defined and possibly symmetric (see Fig. 1). In the case of PSR 1957+20 (the prototype of type I SVPs) we obtain  $\dot{m}_1 \simeq 10^{14} \text{ g s}^{-1}$  for  $R_*/a = 0.0353$ . A lower limit for  $f$  in the case of PSR 1957+20 is obtained by equating  $\dot{m}$  with  $\dot{m}_1$ , i.e.,  $f \gtrsim 0.213/\alpha$ . The upper limit on  $f$  is obtained by the relation  $f \lesssim (0.213/\alpha)(F[1 - R_s/a]/F[1 - R_*/a]) \sim 10/\alpha$ , where we used the shock distance from the companion appropriate for PSR 1957+20 to be  $R_s/a \simeq 1/5$  as suggested by hydrodynamical calculations of the mass outflow fitting the eclipse characteristics of PSR 1957+20 (Tavani and Brookshaw, 1991).

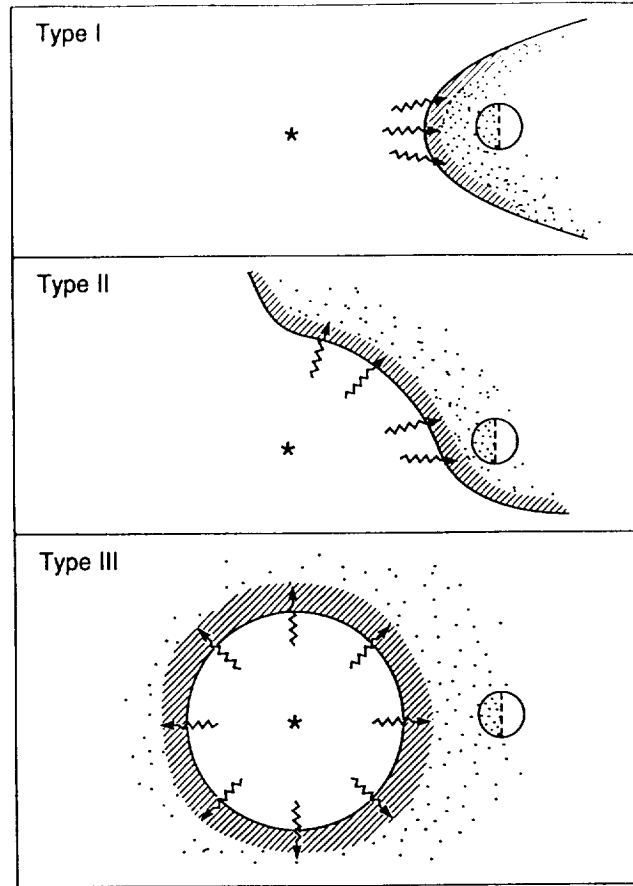


FIG. 1 - Schematic behavior of SVPs of different types (based on the hydrodynamical calculation of Tavani and Brookshaw (1991)). The asterisk denotes the position of the pulsar and the companion star is assumed to be rotating counterclockwise.

SVP's of type II and III are possible when  $\dot{m}$  is larger than  $\dot{m}_1$  and the Coriolis forces together with outflow velocities of order of Keplerian velocities are sufficiently large to produce a large tangential component of the gas pressure near  $R_s$ . This additional component of the gas pressure forces the gas to begin to surround the pulsar in the leading edge of the eclipsing region. The eclipses of type II SVPs are expected to be occasionally non-symmetric with a time variable leading edge of the eclipse (see Fig. 1).

A remarkable example of SVP of type II is offered by PSR 1744-20A which shows symmetric (Nice *et al.*, 1990), non-symmetric (Lyne *et al.*, 1990) and total eclipses. We obtain in this case  $\dot{m}_1 \simeq (3.71 \cdot 10^{12} \text{ g s}^{-1}) \dot{P}_{-20} \Psi^2 / \alpha$ , where  $\Psi = R/R_L \sim 1$  with  $R_L$  the Roche lobe radius, and  $R_s/a \simeq 0.18\Psi$  (Lyne *et al.*, 1990). As in the case of PSR 1957+20 we obtain for PSR 1744-20A the possible range for  $f$ ,  $0.16/\alpha \lesssim f \lesssim 10/\alpha$ , where the upper limit has been obtained by taking  $R_s/a \sim 1/2$ , as suggested by the hydrodynamical calculation of the outflow of PSR 1744-20A (Tavani and Brookshaw, 1991).

### 3. Hidden Millisecond Pulsars

SVPs of type III are obtained if the material near  $R_s$  has sufficient tangential kinetic energy to overcome the pulsar radiation pressure and is able to surround the pulsar completely (see Fig. 1). Eq. (3) shows that this case may occur for a favorable combination of the quantities  $f$ ,  $\alpha$ ,  $\Delta$ , and  $a$ . PSR 1744-20A offers a good example of a SVP of type III during its 'radio-quiet' mode observed several times in 1990 (Lyne *et al.*, 1990; Nice *et al.*, 1990). PSR 1744-20A is an example of a SVP which is able to switch between different eclipse modes, but SVPs which spend most of their time as type III SVPs may exist as well. In this case the central pulsar is completely surrounded by the wind material in the orbital plane that partly accumulates near  $R_s$  and partly escapes from the binary. This class of 'hidden' millisecond pulsars may have their radio emission completely quenched unless the wind material is confined in a thin disk. The shape of the enshrouding material in three dimensions depends on the interplay among gravitational, radiation and pressure forces, and a 'bubble' or a donut-shaped 'torus' can describe the gas configuration surrounding the pulsar. The hydrodynamics together with the stability and time dependent effects influencing the enshrouding material is the subject of intense research (Tavani, 1991c,f) and an account of the results is beyond the scope of this paper. Furthermore, even though the currently known SVPs and the related numerical modelling suggest the existence of a gas configuration enshrouding the pulsar which is optically thin to hard X-rays and gamma-rays (Tavani and Brookshaw, 1991), a more complex configuration may be possible. In the following we will address the main qualitative features concerning the emission of gamma-rays expected from hidden millisecond pulsars assuming that the evaporating material is optically thin to hard X-rays and  $\gamma$ -rays.

### 4. Gamma rays from shock acceleration

Rapidly rotating pulsars are believed to produce a radially expanding relativistic wind of ions and  $e^\pm$  pairs in addition to the comoving Poynting flux of electromagnetic energy in a MHD approximation (e.g., Kennel and Coroniti, 1984; Hoshino *et al.*, 1991). The

MHD pulsar wind is characterized by the Lorentz factor of particles and by the ratio  $\sigma$  of electromagnetic to kinetic energy of wind particles. We can express the Lorentz gamma factor  $\gamma_1$  in terms of a parameter  $\eta$  which gives the efficiency of acceleration and pair production near the pulsar as

$$\gamma_1 = \eta(Ze\Phi_c)/(m_i c^2) \simeq 2.3 \cdot 10^6 \eta(Z/A)(\dot{P}_{-20}/P_{-3}^3)^{1/2}. \quad (4)$$

where  $\Phi_c \sim (2\pi R_p/cP)^2(2\mu/R_p^3)R_p$  is the voltage across open field lines of a pulsar of magnetic moment  $\mu$ , and  $Z/A$  is the average ratio of charge over mass number of the wind particles. The quantity  $\sigma$  is

$$\sigma = B^2/4\pi c^2[N_i m_i \gamma_i + (N_{e+} + N_{e-})m_e \gamma_{e\pm}] \quad (5)$$

where  $N_i, m_i, \gamma_i$  and  $N_{e\pm}, m_e, \gamma_{e\pm}$  are the number densities, masses and relativistic Lorentz factors for the ions and  $e^\pm$  pairs, respectively. In the MHD approximation,  $\gamma_{e\pm} = \gamma_i = \gamma_1$ . Detailed models for the Crab nebula require  $\sigma \sim 10^{-2} - 10^{-3}$  (Kennel and Coroniti, 1984), and  $\eta \sim 0.3$  (Hoshino *et al.*, 1991) which implies a value of  $\gamma_1$  between  $10^{5.3}$  (fully stripped iron) and  $10^{5.6}$  (protons).

The pulsar wind of relativistic particles and Poynting flux interacts with the inner boundary of the SVP ‘bubble’ or ‘torus’ of Fig. 1 and a relativistic shock ensues. For simplicity, we will assume that the region around the shock region is sufficiently dense that the e.m. waves and plasma in the pulsar wind do not penetrate the mass outflow, and that the magnetic field is transverse to the shock normal at  $r_s$ . Under these conditions, diffusive Fermi acceleration (e.g., Ellison *et al.*, 1990) is not applicable, and the shock is transverse. The characteristics of particle acceleration depend on the details of the relativistic shock and several models are currently being investigated (Tavani, 1991f).

One sufficiently developed model of shock acceleration based on resonant absorption of magnetosonic waves by positrons near the ion reflecting region has been recently applied to the study of gamma-ray emission from PSR 1957+20 (Arons and Tavani, 1991). The radiation spectrum emitted downstream depends on the physical processes regulating the efficiency of synchrotron, inverse Compton scattering and non-thermal emission of the relativistic shock. The typical synchrotron energy is of order  $E_{syn} \simeq (10 \text{ keV}) \gamma_{e\pm}^2 B_P \sqrt{\sigma/(1+\sigma)}$ , where  $\gamma_{e\pm} = 10^6 \gamma_{e\pm,6}$  and  $B_P$  is equal to the magnetic field of an ideal Poynting flux assumed to carry all the spindown energy of the pulsar. Typically,  $B_P = \mu/(r_{ic}^2 r) \simeq (440 \text{ G}) B_9/(P_{-3}^2 r_{s,11})$ , with  $B_9$  the surface magnetic field in units of  $10^9 \text{ G}$ , and  $r_{s,11} = r_s/(10^{11} \text{ cm})$ .

The radiation spectrum expected from the relativistic shock with ion-induced acceleration of positrons has been shown to have a photon index  $s \sim 2$  (Hoshino *et al.*, 1991). The effective synchrotron emissivity of the shock is a power law  $j_e^{(b)}/\epsilon \propto \epsilon^{-2}$  (in units of photons  $\text{sec}^{-1} \text{ cm}^{-3}$ ), extending from  $\epsilon_1^{(b)}$  to  $\epsilon_s^{(b)}$ . By equating the radiation loss timescale with the ion-induced acceleration timescale we obtain a range for the upper energy cutoff  $10 \text{ MeV} \lesssim \epsilon_s^{(b)} \lesssim 10 \text{ GeV}$  for different choices of  $\gamma_1$  and  $\sigma$ . As an example, an application to PSR 1957+20 of the ion-induced acceleration model with pulsar wind parameters for

the Crab nebula gives  $\epsilon_s^{(b)} \sim 3$  MeV (Arons and Tavani, 1991). If ions contribute to a substantial part of the pulsar wind energy, the radiation spectrum is expected to be a power law of index  $s$  from a few keV to tens or hundreds of GeV. The corresponding heating on the surface of the irradiated companion yields  $10^{-3} \lesssim f \lesssim 10^{-2}$ . Alternately, if ions do not appreciably contribute to the pulsar wind kinetic energy and therefore are not effective in pair acceleration near  $r_s$ , most of the pulsar wind energy is expected to be radiated at lower energies peaked around  $E_{syn}$  (Hoshino *et al.*, 1991) unless an additional shock acceleration mechanism (such as shock-drift acceleration) operates. The corresponding spectrum is expected to be in the X-ray energy range and  $1 \lesssim f \lesssim 0.1$ . For energies below  $\epsilon_1$ , the spectrum is cut off, since the emission comes from the low energy tail of the nonthermal part of the particle spectrum, and from the Maxwellian pairs at energies less than  $\gamma_1 m_\pm c^2$ , with  $\epsilon_j \propto \epsilon^{4/3}$  (e.g., Jones and Hardee, 1979).

## 5. Observational Consequences

Hidden millisecond pulsars produce a gamma-ray yield larger than in the case of isolated pulsars, and they are therefore interesting for interpreting galactic gamma-ray sources. The  $\gamma$ -ray flux from hidden millisecond pulsars at the distance  $D$  can be estimated for a power-law emission as follows ( $\epsilon$  is the photon energy)

$$\frac{dN(E > \epsilon)}{dt} \sim (3 \cdot 10^{-4} \text{ ph. cm}^{-2} \text{ s}^{-1}) \frac{L_{p,36}}{D_{kpc}^2} \frac{\tilde{\epsilon}}{0.2} \frac{1 \text{ MeV}}{\epsilon} \quad (6)$$

where  $\tilde{\epsilon}$  is the efficiency of conversion of pulsar wind energy into radiation (Hoshino *et al.*, 1991),  $L_{p,36} = L_p / (10^{36} \text{ erg s}^{-1})$ , and  $D_{kpc} = D / (1 \text{ kpc})$ .

The detectability of gamma-rays from a hidden millisecond pulsar depends crucially on the ratio  $L_{p,36} / D_{kpc}^2$ . In the case of GRO detectors, we notice that hidden pulsars would be detectable by OSSE, COMPTEL and EGRET for a normal pointing time of two weeks if  $L_{p,36} / D_{kpc}^2$  were larger or equal to  $\sim 1, 0.2$ , and  $0.01$ , respectively.

### 5.1 Hidden Pulsars with Main Sequence Companions

Low-mass X-ray binaries (LMXBs) are believed to be the most probable progenitor of binary millisecond pulsars (e.g., Tavani, 1991a). However, no galactic binary millisecond pulsar has yet been discovered with a main sequence companion (e.g., Tavani, 1991e) even though the majority of LMXBs have orbital periods proper to binaries with main sequence companions (e.g., Ritter, 1990). This might be due to the effect of Doppler spread of the radio signal in orbits with orbital periods  $P_{orb} \lesssim 6$  hrs. However, millisecond pulsars with main sequence companions satisfy Eq. (3) with  $\Delta_{-2} \gtrsim 1$ , and they may be hidden SVPs. Hidden SVPs with main sequence companions may be revealed by the X-ray/ $\gamma$ -ray emission from the radio-obscuring ‘bubble’ and, possibly, by an optical modulation of the irradiated companion star if the inclination angle is favorable. The luminosity of the companion star reprocessing the secondary radiation from the pulsar wind is  $L \simeq (4 \cdot 10^{33} \text{ erg s}^{-1}) \dot{P}_{-20} I_{45} \Delta_{-2} / P_{-3}^3$  with a photospheric temperature  $T \simeq (1.5 \cdot 10^4 \text{ K}) \dot{P}_{-20}^{1/4} P_{-3}^{-3/4} a_{11}^{-1/2}$ . Main sequence companion stars of millisecond pulsars

would appear brighter and ‘bluer’ compared to similar undisturbed stars.

### 5.2 Interpretation of COS-B sources

Even though the pulsed and unpulsed radio emission of hidden SVPs is probably completely blocked, they can be visible in the X-ray/ $\gamma$ -ray band and, indirectly, in the optical band because of irradiation of the companion star (see Sect. 5.1). The radiation spectrum originating from the ‘bubble’ surrounding a SVP can be a power-law extending to energies  $\sim 10$  GeV, and hidden SVPs can be important for the interpretation of X-ray and  $\gamma$ -ray sources already discovered by COS-B and/or to be discovered by the Gamma Ray Observatory (GRO). The association of an X-ray and/or  $\gamma$ -ray source with a ‘blue’ companion star possibly showing optical modulation provides a well defined signature for the existence of hidden SVPs (Tavani, 1991c). The detectability of this association depends on details such as the inclination angle, and the amount of shadowing of the optical emission. It is however worthwhile to search for optical modulations in the field of known  $\gamma$ -ray sources (e.g., unidentified COS-B sources, Swanenburg *et al.*, 1981).

Furthermore, again depending on the geometry, even the gamma-rays can be modulated with an orbital period by scattering and absorbing material related to either the companion star itself or to density enhancements in the bubble/ torus surrounding the pulsar. A well defined signature for a successful association of gamma-ray sources with binary systems is therefore the existence of modulations in the gamma-ray flux with periods of few hours. A search of orbital period modulations in the gamma-rays from COS-B-like sources has not been systematically attempted before, and a periodicity search of GRO and COS-B data is strongly urged. Folding gamma-ray data with given periodic patterns may significantly increase the signal to noise ratio.

### 5.3 Gamma rays from globular clusters

A relatively large number of single and binary millisecond pulsars ( $\sim 25$ ) has been discovered in globular clusters (e.g., Tavani, 1991e), possibly as a consequence of the high probability of stellar encounters in dense cluster cores. A remarkable example of a globular cluster which harbors many millisecond pulsars ( $\sim 10$ ) is 47 Tucanae (Manchester *et al.*, 1991). It is therefore natural to expect that a relatively large number of pulsars in globular clusters are hidden, and that a detectable gamma-ray or optical signal can be used to deduce their existence. We note here that a class of ‘blue stragglers’ as those discovered in NGC 6397 (Auriere, Ortolani and Lauzeral, 1990) and in 47 Tucanae (Paresce *et al.*, 1991) might contain millisecond pulsars whose irradiation alter the properties of their companions (Tavani, 1991b,d). The existence of pulsar-driven blue stragglers is particularly interesting in globular clusters where the majority of stars are main sequence (Tavani, 1991d).

We note that the gamma-ray flux from individual and not enshrouded pulsars in globular clusters is too low to be detected by current gamma-ray detectors. However, the shock acceleration mechanism of hidden powerful pulsars enhances the gamma-ray yield for each single source, and single (in the case of EGRET) or collective emission from hidden pulsars might be detected by GRO. A periodicity search in a range of a few hours

might enhance the discovery probability. We estimated the number of sources necessary to make globular clusters detectable by the GRO instruments. We assumed the photon flux from Eq. (6) and an average  $L_{P,36} = 1$ . For 47 Tucanae we obtain the minimum numbers (21, 4, 1) for OSSE, COMPEL and EGRET, respectively. For Terzan 5 we obtain (50, 10, 3), and for the core collapsed cluster NGC 6397 we estimate the minimum numbers in the range (5, 1, 1).

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